Report from the RHIC II Heavy Flavor Working Group

Conveners: Ramona Vogt, Thomas Ullrich, Tony Frawley

Tony Frawley
RHIC II Workshop
November 11-12, 2005

Motivation for Heavy Flavor Measurements

Our goal is to understand the properties of the hot, dense matter produced in heavy ion collisions.

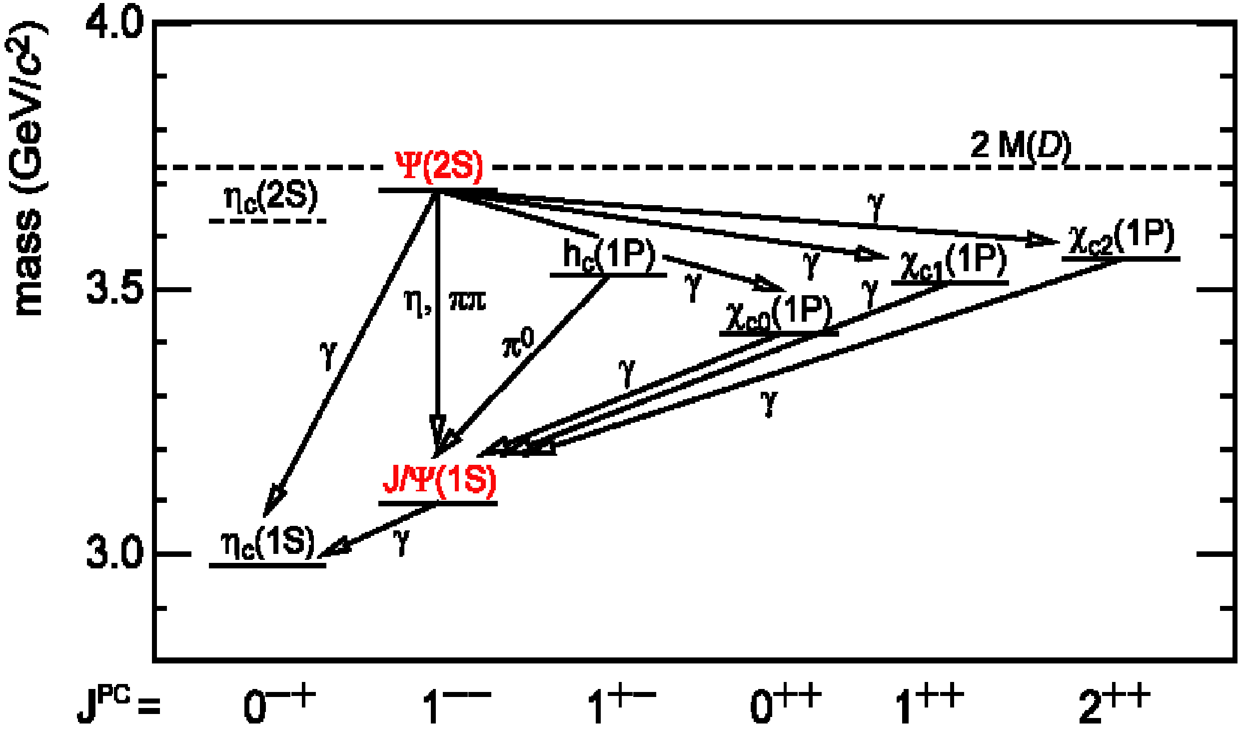
Since charm and bottom quarks are produced in the **initial parton collisions**, their interactions with the final state medium modify their observed properties.

- $c\bar{c}$ and $b\bar{b}$ bound states (**quarkonia**) can teach us about deconfinement
- c and b (**open charm**) energy loss can teach us about energy density

There are, of course, a few complications.

Quarkonia – What Can We Learn?

- Key Idea: Melting in the plasma
  - Color screening of the static potential between heavy quarks produces J/ψ suppression (originated with Matsui and Satz).
  - Suppression of states is determined by **T/T_C** and their **binding energy**.



	$E_{binding}$ (GeV)
J/ψ	0.64
ψ’	0.05
χ_c	0.2
ϒ (1S)	1.1
ϒ (2S)	0.54
ϒ (3S)	0.31

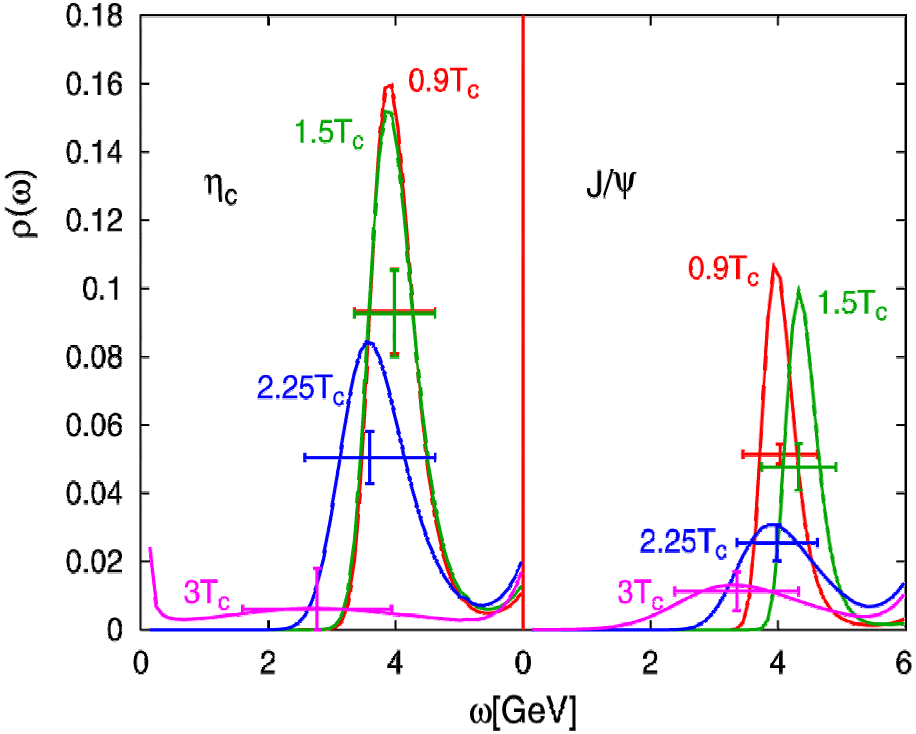
- Sequential disappearance of states as T increases:

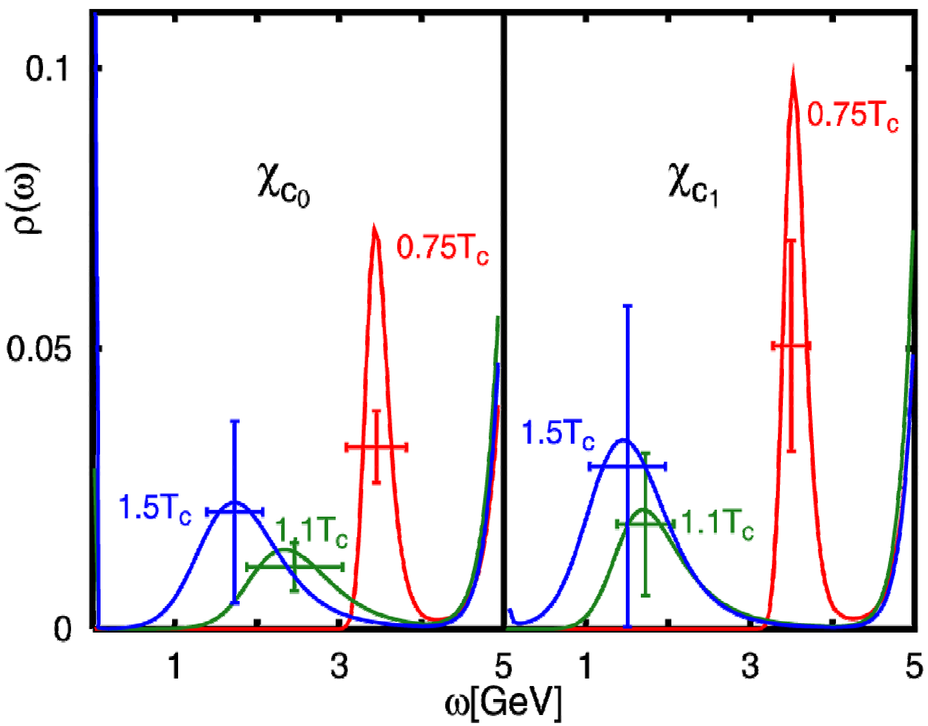
  ⇒ Color screening ⇒ Deconfinement

  ⇒ QCD thermometer ⇒ Properties of QGP

Quarkonia – Lattice QCD

Example spectral functions (Datta et al., Phys Rev D 69 (2004) 094507)





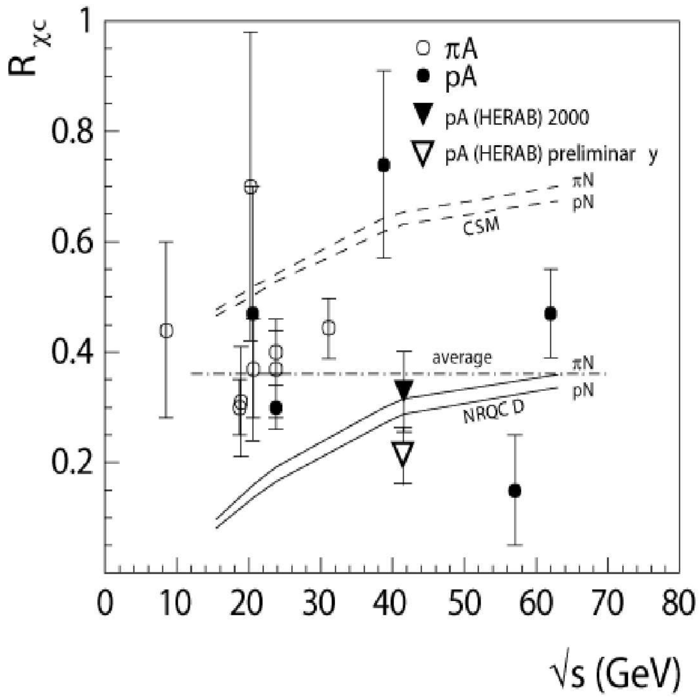
J/ψ not affected by medium below ~ 1.5 T_c , **may persist beyond 2 T_c** .

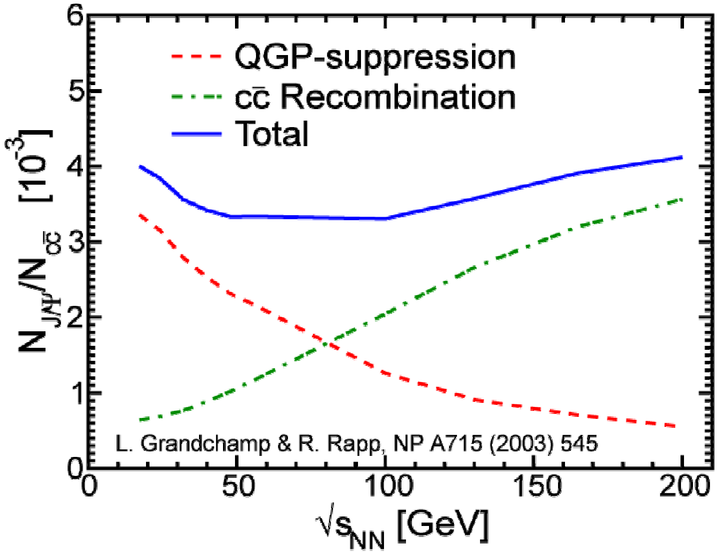
χ_c **strongly modified by ~ 1.1 T_c** .

Bottomonium - **more work** needed to establish where medium effects set in.

Collision with thermal gluons, ⟨p⟩ ~ 3 T_c can lead to earlier dissociation: $dN_{J/\psi}/dt = -N_g \langle \sigma_{dis} \rangle$

Quarkonia – Other Complicating Effects in AA





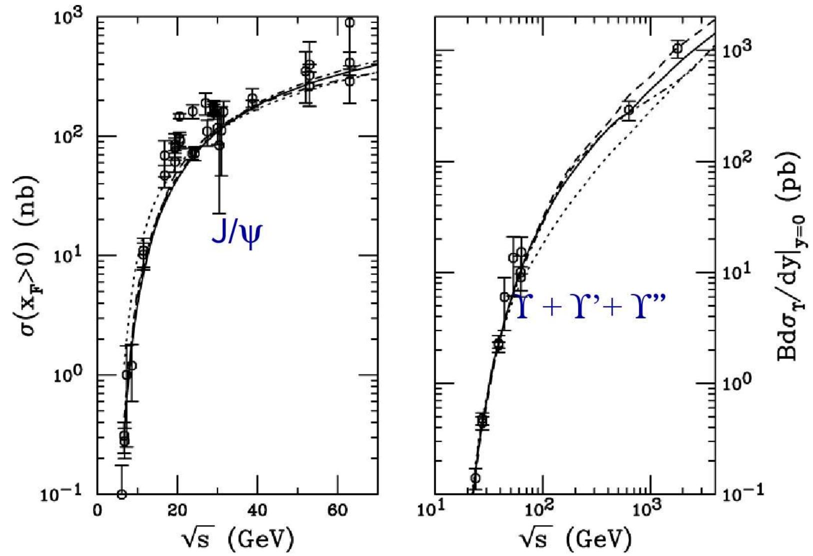
- Feed down:
  - Large from χ_c states (30-40% ?)
  - Not well measured in hadronic collisions
  - Unknown at RHIC energies
- Other sources of quarkonium production
  - Thermal charm production
    - Small at RHIC – larger at LHC ?
  - Dynamic coalescence
    - coalescence: $\bar{c}+c \rightarrow J/\psi$
    - $\Rightarrow$ narrower y and softer p_T distributions
- Energy loss at high-p_T
- Comover absorption in hadronic gas
  - $J/\psi + \pi\ (\rho) \rightarrow D\bar{D}$ (negligible for Υ)
- Initial state gluon shadowing ($\Rightarrow$ later)

Many effects need to be understood to extract pure “suppression” mechanism

Quarkonia – Baseline Theory (pp/dA)

- Need properly "normalized" Quarkonia baseline
  - pp ⇒ production baseline
  - d+Au ⇒ cold matter effects (absorption, shadowing)
- pp
  - Color Evaporation Model (CEM)
  - Quarkonium production treated as fraction of all $\bar{Q}Q$ pairs below $\bar{H}H$ threshold
  - CEM taken to NLO (Gavai et al., G. Schuler and R.Vogt)
  - Parameters adjusted to existing data

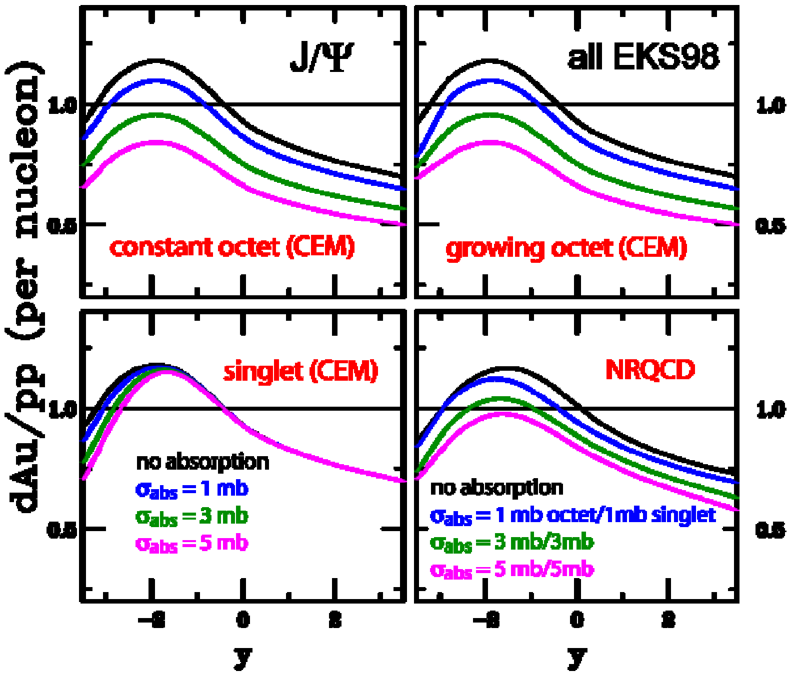
	Direct production ratio
J/ψ	0.62
ψ'	0.14
χ_{c1}	0.60
χ_{c2}	0.99
ϒ (1S)	0.52
ϒ (2S)	0.33
ϒ (3S)	0.20

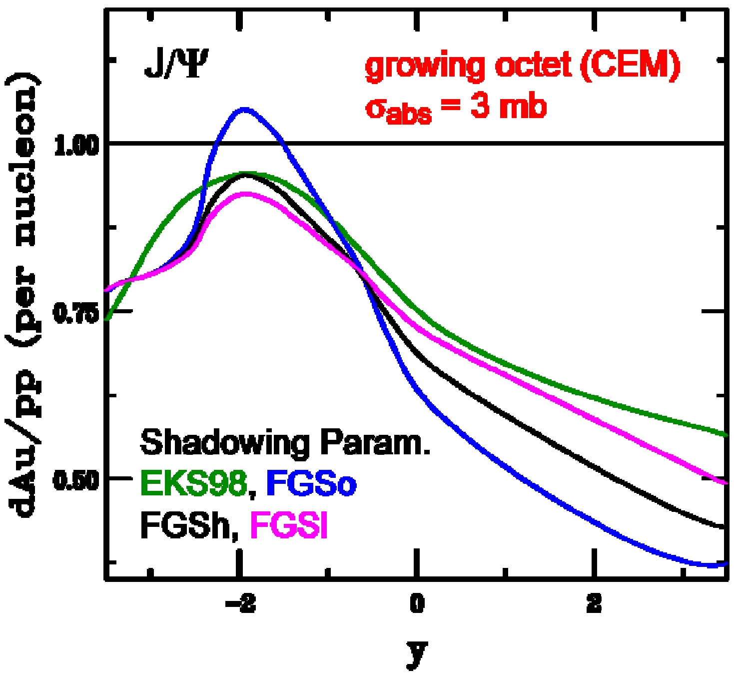


hep-ph/0412158

Quarkonia – Baseline Theory (pp/dA)

- dAu
  - Nuclear Absorption
    - Breakup of quarkonia in the final state
    - Depends if produced as color singlet or octet
  - Shadowing
    - Modification of PDFs in the nucleus w.r.t. free nucleon
    - NB: y-distributions more sensitive than p_T





R. Vogt, RHIC-II Science Workshop

Open Heavy Flavor – What Can We Learn?

Open Heavy Flavor Mesons: D^0, D^*, $D^{\pm}$, D_s, B

- Key Idea: Study interaction with hot and dense media
  - Yields
  - Spectra
  - Correlations
- High-p_T suppression $\Rightarrow$ Density of medium, E-Loss mechanism
- Low-p_T flow, spectra $\Rightarrow$ Thermalization ?

  $\Rightarrow$ Transport properties of the medium
- Charm-Charm, Charm-Hadron, J/ψ-Hadron Correlations:
  - Low-p_T $\Rightarrow$ Thermalization ?
  - High-p_T $\Rightarrow$ Tomography of medium

Study of heavy flavor $\Rightarrow$ Properties of QGP (Density, Thermalization)

Open Heavy Flavor – Energy Loss Models

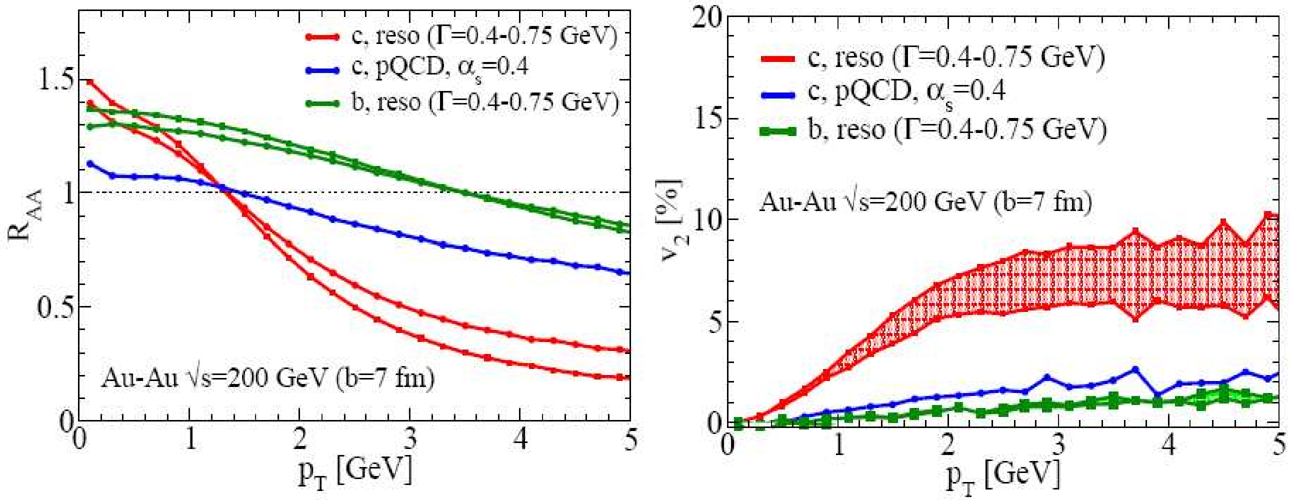
Heavy quarks can lose energy in the medium by two processes:

- **Elastic collisions with light partons in the medium (collisional)**
- **Gluon bremsstrahlung (radiative)**

There are detailed pQCD radiative energy loss calculations (Djordevic et al., Armesto et al.) for heavy quarks that use energy densities that are **constrained by light hadron energy loss data**. **We will see these compared with data later, so I will say no more now.**

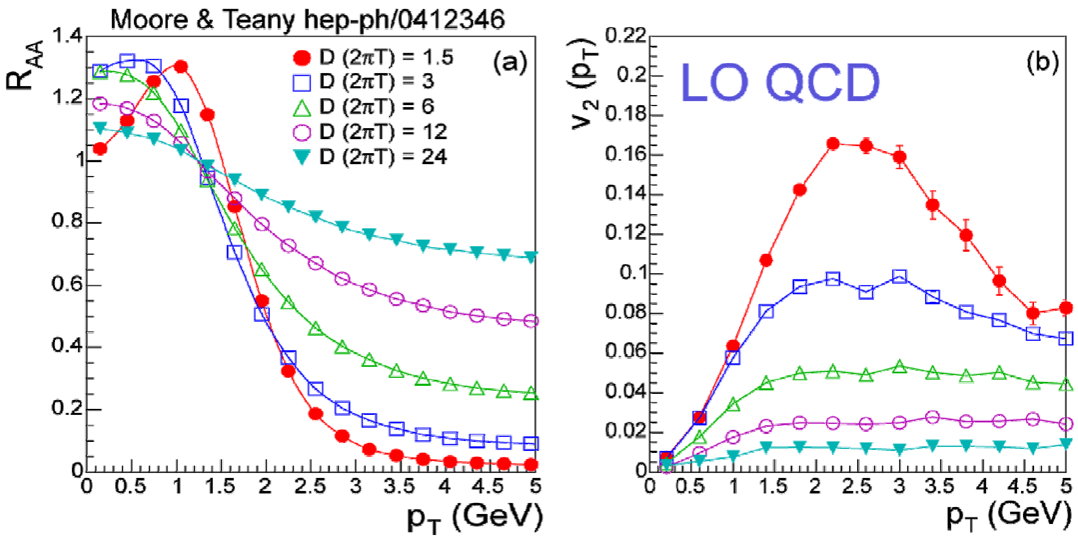
Calculations of the suppression and elliptic flow in which collisional energy loss processes dominate are also available. **Examples on the next slide.**

Van Hees & Rapp, PRC 71, 034907: resonant heavy-light quark scattering via scalar, pseudoscalar, vector, and axial vector D-like-mesons



Isotropic resonant scattering gives larger cross sections than pQCD elastic scattering - note b!

Moore & Teeny: Study of diffusion coefficient in QGP, D = T/Mη (η drag coefficient), using a Langevin model

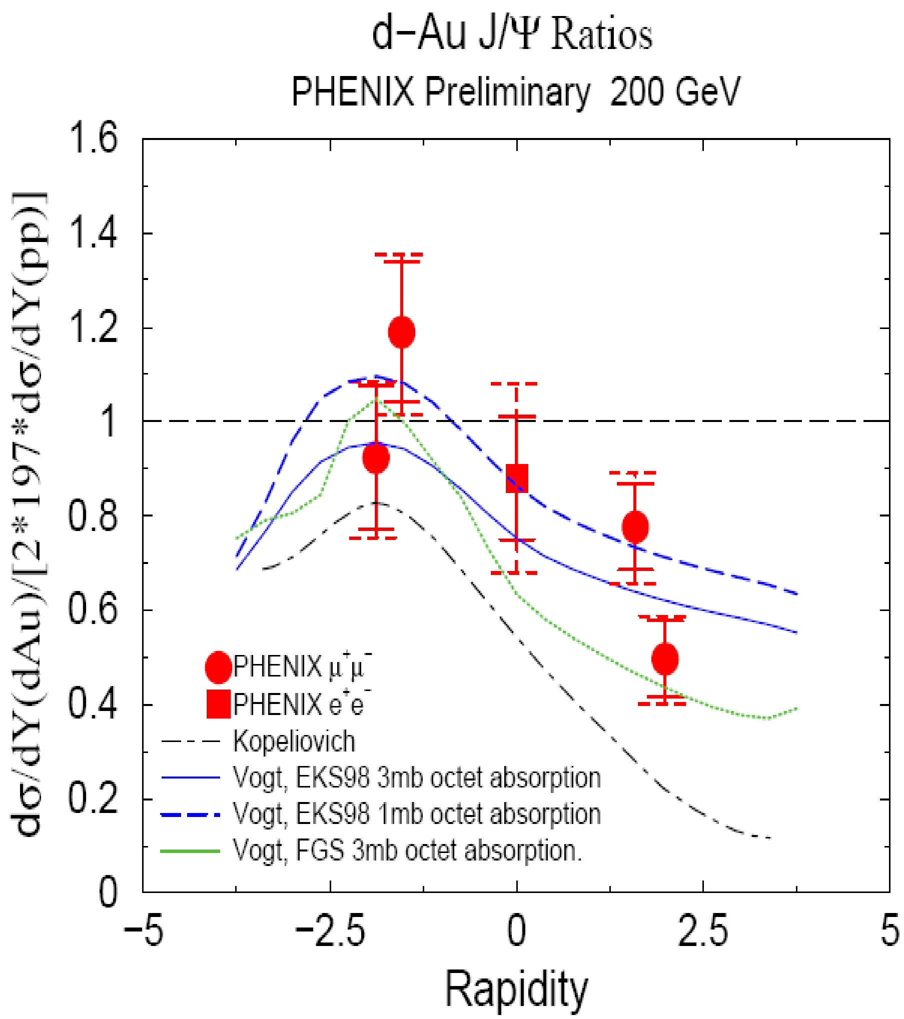


Strong charrm suppression and large v_2 need huge drag coefficient

What have we learned at RHIC so far?

RHIC Results – dAu J/ψ Baseline

- Study of $J/\psi \to ee$ and $\mu\mu$ in d+Au
  - EKS98 calculation does a good job on minimum bias data.
  - The data are best reproduced by a small absorption cross section (~ 1 mb).



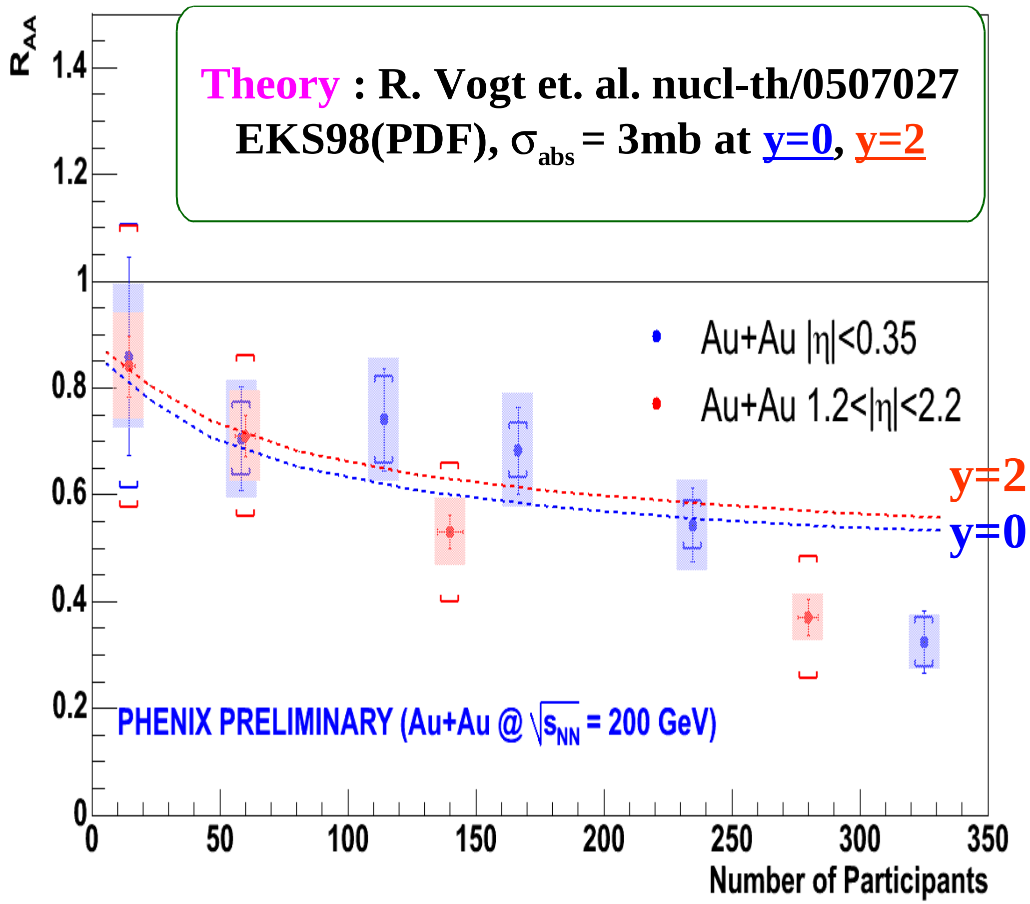
V. Ciancolo, RHIC II Workshop

- Issues:
  - Lack of statistics
  - Only J/ψ measurement available so far

⇒ Need more statistics and data on ψ', χ_c, and ϒ states

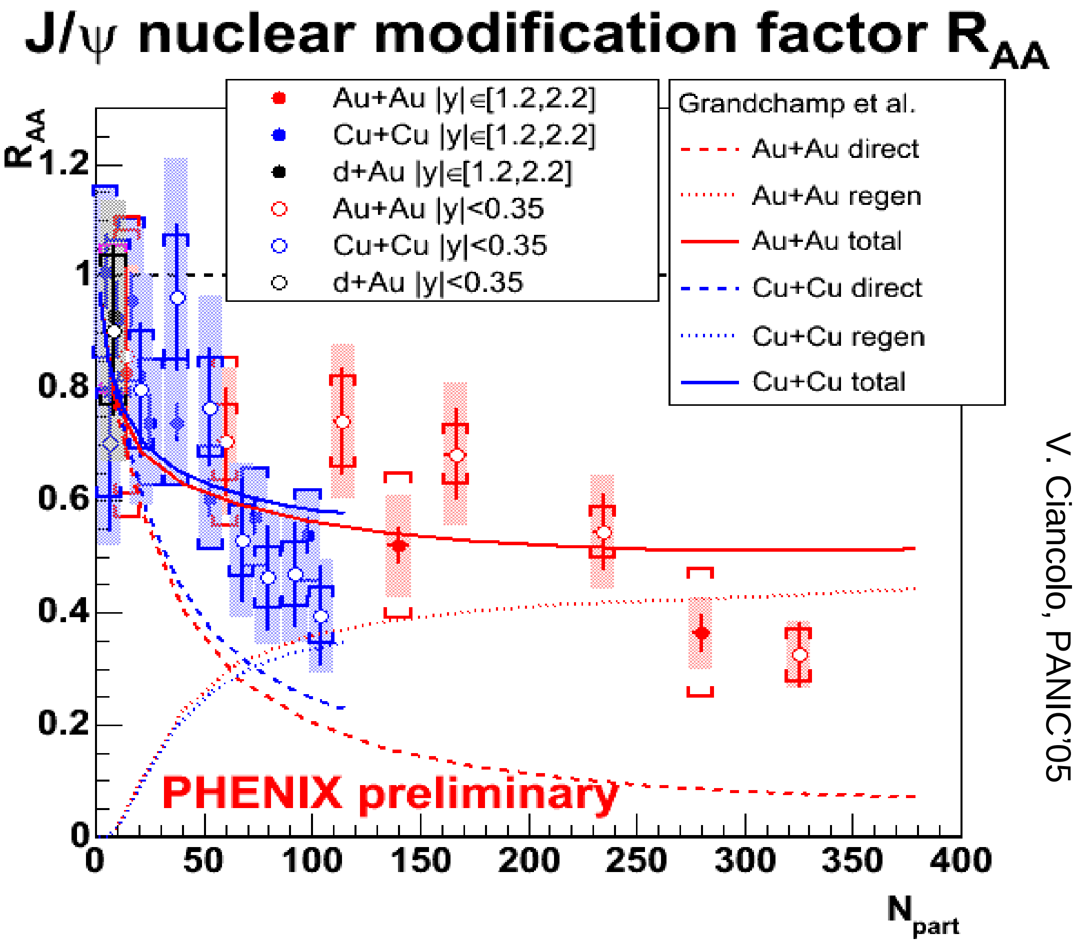
RHIC Results – J/ψ Suppression

- Study of $J/\psi \rightarrow ee$ and $\mu\mu$ in Au+Au and Cu+Cu
  - Yield is suppressed compared to that in p+p collisions
  - Suppression is larger for more central collisions.
  - Suppression beyond cold nuclear matter for most central collisions, even for $\sigma_{abs} \sim 3$ mb.



RHIC Results – J/ψ Suppression

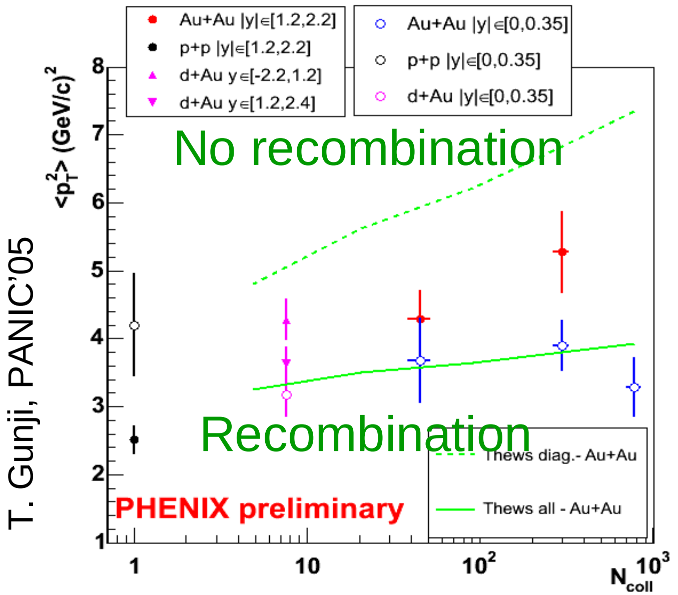
- Study of J/ψ → ee and μμ in Au+Au and Cu+Cu
  - Yield is suppressed compared to that in p+p collisions
  - Suppression is larger for more central collisions.
  - Suppression beyond cold nuclear matter for most central collisions, even for σ_{abs} ~ 3 mb.
  - Coalescence models tend to underpredict the suppression somewhat too, but **dominated** by coalescence.

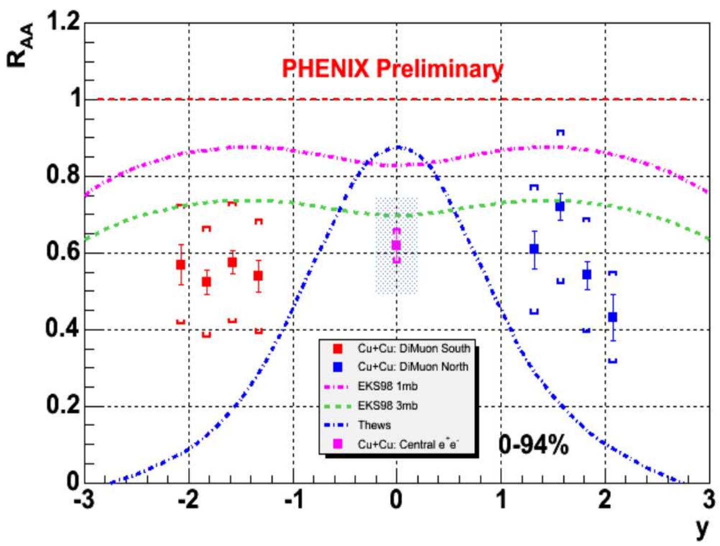


- Issues:
  - Lack of statistics
  - Only J/ψ measurement is available so far

⇒ Need more statistics and data on ψ’, χ_c, and ϒ states

RHIC Results – J/ψ Suppression





Recombination models predict narrow p_T and rapidity distribution:

- $\langle p_T^2 \rangle$ vs. $N_{collisions}$
  - Predictions of recombination model match better.
- R_{AA} vs. Rapidity
  - No significant change in rapidity shape compared to p+p result.

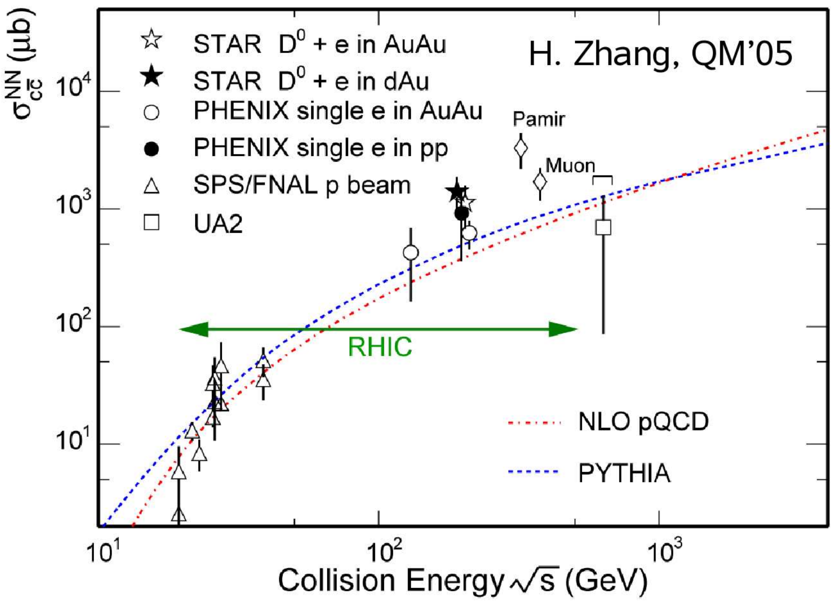
Recombination compensates suppression?

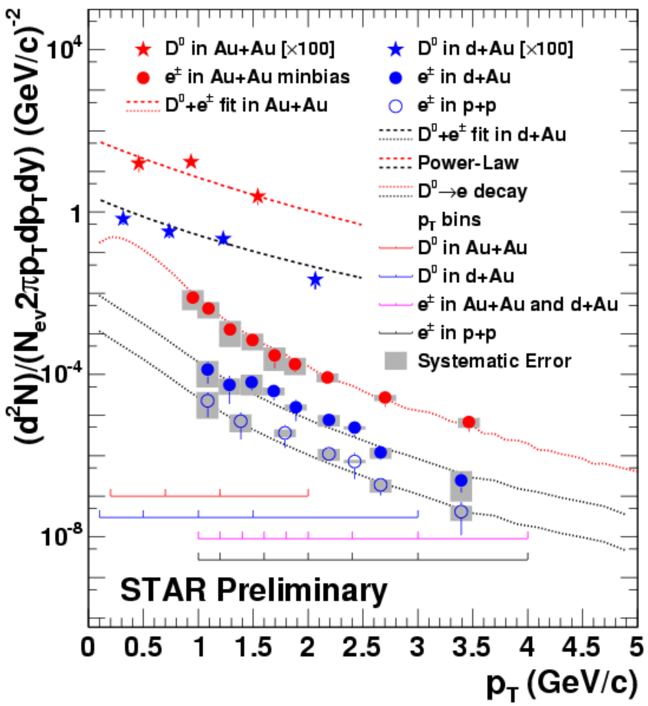
- Issues:
  - Charm rapidity distributions at RHIC are open questions
  - Require more data on √s, A dependence

Need more statistics, J/ψ v_2 for mechanism studies.

RHIC Results – Charm Cross Section

- Study of D mesons (Kπ combinations/event mixing) and non-photonic single electrons (from semileptonic D decays)
  - Cross section 2-4 × larger than predictions from NLO



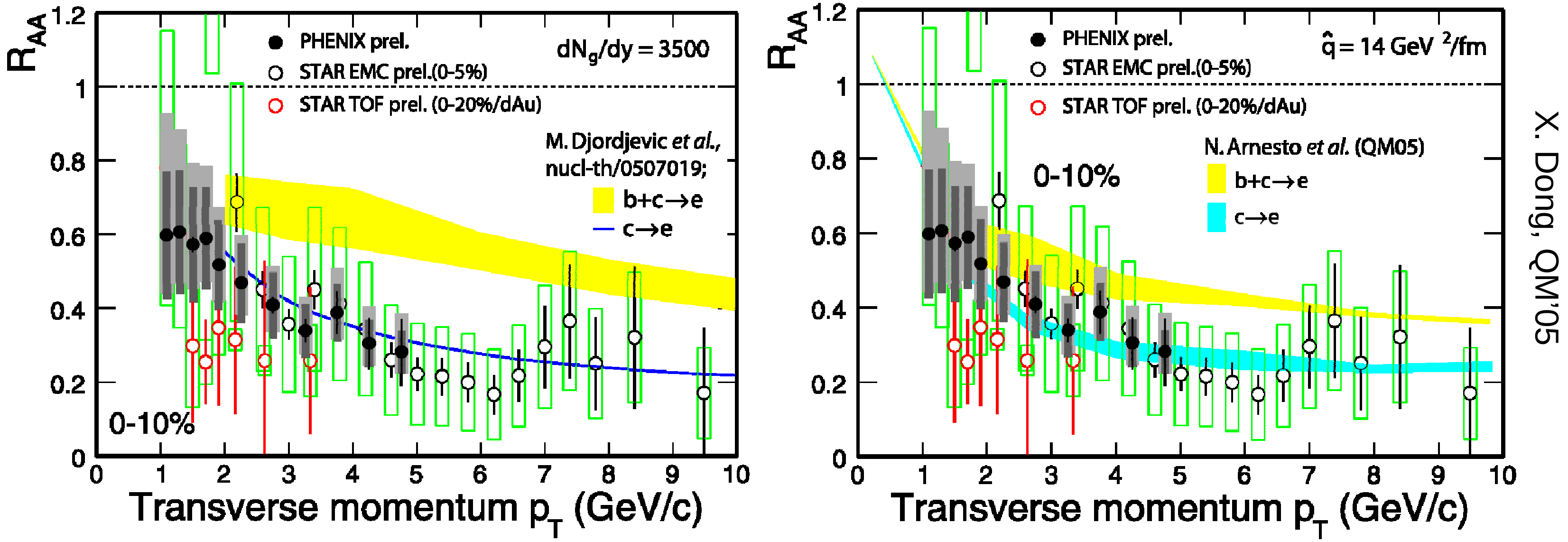


- Issues:
  - D mesons: large background
  - Non-photonic electrons: $\sigma_{measured}/\sigma_{cc}$ ~ 15%

⇒ Need direct measurement of D mesons (via K π), need electrons to low p_T

RHIC Results – Energy Loss

- Study of non-photonic single electrons (from semileptonic D decays)
  - First evidence of strong suppression of charm at high-p_T - **surprise!**
  - Challenge to existing E-loss paradigm (collisional E-loss important?)

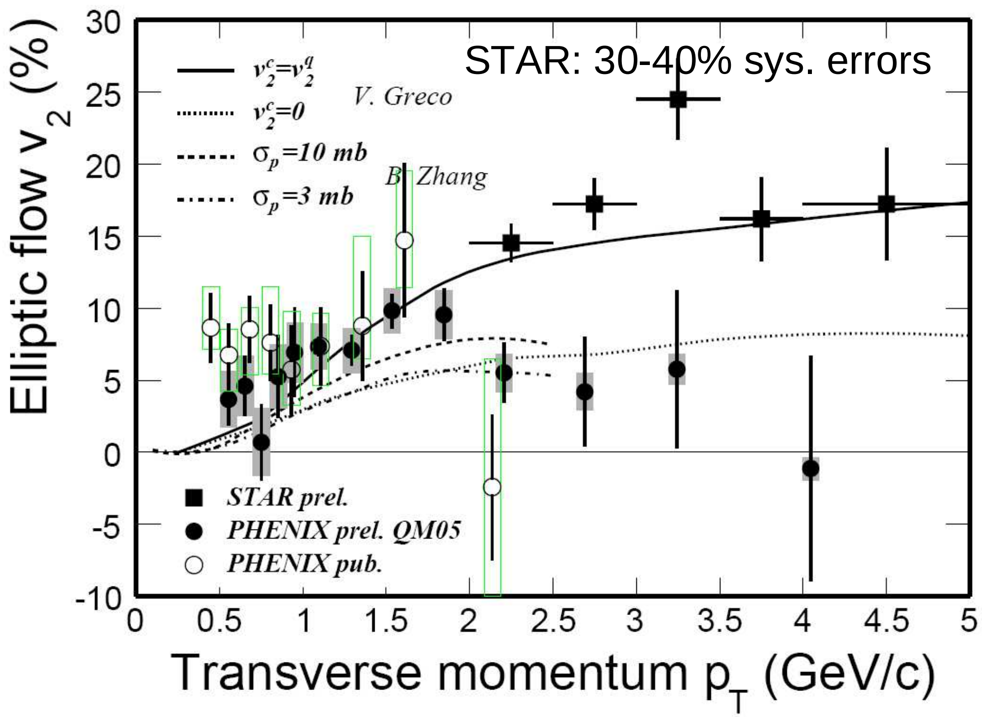


- Issues:
  - Statistics at high-p_T limited, uncertainties due to photonic background at low p_T
  - Cannot deconvolute contributions from charm and bottom

⇒ Need direct measurement of high-p_T D mesons (via K π)
and B mesons (via J/ψ)

RHIC Results – Charm Flow

- Study of non-photonic single electrons (from semileptonic D decays)
  - See strong charm elliptic flow for $p_T < 2$ GeV/c
  - Measurements from STAR & PHENIX differ at higher p_T



X. Dong, QM'05

- Issues:
  - Statistics limited
  - Uncertainties due to photonic background
  - Large sys errors
  - Cannot deconvolute contributions from charm and bottom
- Need a lot more yield.
- Reduce backgrounds with displaced vertex measurement.
- Need direct measurement of D mesons (via K π) v_2

Interesting start - how do we proceed?

RHIC-II - Facing the Challenge

- Addressing the requirements:
  - RHIC II: increased luminosity (RHIC II $\approx$ 10 $\times$ RHIC)
    - Note: collision diamond σ = 20 cm at RHIC and σ = 10 cm at RHIC II $\Rightarrow$ gain in usable luminosity is larger than "nominal" increase
  - PHENIX & STAR: more powerful upgraded detectors crucial to the Heavy Flavor physics program - completed in mid/near term ~5 years.
- STAR:
  - DAQ upgrade increases rate to 1 KHz, triggered data has ~ 0 dead time.
  - Silicon tracking upgrade for heavy flavor, jet physics, spin physics.
  - Barrel TOF for hadron PID, heavy flavor decay electron PID.
  - EMCAL + TOF J/ψ trigger useful in Au+Au collisions.
  - Forward Meson Detector
- PHENIX:
  - Silicon tracker for heavy flavor, jet physics, spin physics.
  - Forward muon trigger for high rate pp + improved pattern recognition.
  - Nose cone calorimeter for heavy flavor measurements.
  - Aerogel + new MRP TOF detectors for hadron PID.
  - Hadron-blind detector for light vector meson e^+e^- measurements.

RHIC-II – Open Heavy Flavor Improvements

- With detector upgrades (both PHENIX and STAR):
  - Dramatically reduce backgrounds for all open charm, open beauty signals using displaced vertex measurement.
  - Separate open charm and beauty statistically using displaced vertex.
  - Separate B $\rightarrow$ J/ψ from prompt J/ψ using displaced vertex.

- And with the luminosity upgrade:
  - Extend open charm and beauty R_{AA} measurements to high p_T. What is the energy loss well above the thermalization region?
  - Measure D & semileptonic charm and beauty decay v_2 to high p_T. See the transition from thermalization to jet energy loss for charm.
  - Measure open charm correlations with open charm or hadrons.

RHIC-II - Quarkonia Improvements

- With detector upgrades:
  - J/ψ from B decays with displaced vertex measurement (both).
  - Reduce $J/\psi \rightarrow \mu\mu$ background with forward μ trigger in PHENIX.
  - Improve mass resolution for charmonium and resolve Υ family.
  - See γ in forward calorimeter in front of muon arms (PHENIX) and in FMD in STAR $\rightarrow \chi_c$.

- And with the luminosity upgrade:
  - J/ψ R_{AA} to high p_T. Does J/ψ suppression go away at high p_T?
  - J/ψ v_2 measurements versus p_T. See evidence of charm recombination?
  - Υ R_{AA}. Which Upsilons are suppressed at RHIC?
  - Measure $\chi_c \rightarrow J/\psi+\gamma$ R_{AA}. Ratio to J/ψ?
  - Measure Ψ' R_{AA}. Ratio to J/ψ?
  - Measure $B \rightarrow J/\psi$ using displaced vertex - independent B yield measurement, also get background to prompt J/ψ measurement.

Where does the LHC fit in this picture?

RHIC II

Beams: **p to U**
All combinations $\sqrt{s}$ = **22-200 GeV**

Central Au+Au: T ~ 2 T_c

Detectors:
PHENIX STAR eRHIC detector?

12 weeks / year physics (split runs)
Average luminosity 7 * 10^{27} cm^{-2} s^{-1}
Au+Au lum/year 18,000 μb^{-1}

$Lint_{RHIC}/Lint_{LHC}$ = **36**

N_{cc} ~ 10 N_{bb} ~ 0.05 (central)

LHC

Beams: **p to Pb**
p+p $\sqrt{s}$ = **14 TeV**
p+Pb $\sqrt{s}$ = **8.8 TeV**
Pb+Pb $\sqrt{s}$ = **5.5 TeV**

Central Pb+Pb: T ~ 3.5 T_c

Detectors:
ALICE ATLAS CMS

4 weeks / year physics
Average luminosity 5 * 10^{26} cm^{-2} s^{-1}
Pb+Pb luminosity/year 500 μb^{-1}
$\sigma(J/\psi)_{LHC} = \sigma(J/\psi)_{RHIC}$ * **13**
$\sigma(Y)_{LHC} = \sigma(Y)_{RHIC}$ * **55**

N_{cc} ~ 115 N_{bb} ~ 5 (central)

RHIC II

Beams: **p to U**

All combinations $\sqrt{s}$ = **22-200 GeV**

Central Au+Au: T ~ 2 T_c

Detectors:

PHENIX STAR eRHIC detector?

12 weeks / year physics (split runs)

Average luminosity 7 * 10^{27} cm^{-2} s^{-1}

Au+Au lum/year 18,000 μb^{-1}

$Lint_{RHIC}/Lint_{LHC}$ = **36**

N_{cc} ~ 10 N_{bb} ~ 0.05 (central)

LHC

Beams: **p to Pb**

p+p $\sqrt{s}$ = **14 TeV**

p+Pb $\sqrt{s}$ = **8.8 TeV**

Pb+Pb $\sqrt{s}$ = **5.5 TeV**

Central Pb+Pb: T ~ 3.5 T_c

Detectors:

ALICE ATLAS CMS

4 weeks / year physics

Average luminosity 5 * 10^{26} cm^{-2} s^{-1}

Pb+Pb luminosity/year 500 μb^{-1}

$\sigma (J/\psi)_{LHC} = \sigma (J/\psi)_{RHIC}$ * **13**

$\sigma (Y)_{LHC} = \sigma (Y)_{RHIC}$ * **55**

N_{cc} ~ 115 N_{bb} ~ 5 (central)

RHIC II

Beams: **p to U**
All combinations $\sqrt{s}$ = **22-200 GeV**

Central Au+Au: $T \sim 2\,T_c$

Detectors:
PHENIX STAR eRHIC detector?

12 weeks / year physics (split runs)
Average luminosity 7 * 10^{27} $cm^{-2}\,s^{-1}$
Au+Au lum/year 18,000 μb^{-1}

$Lint_{RHIC}/Lint_{LHC}$ = **36**

$N_{cc} \sim 10$ $N_{bb} \sim 0.05$ (central)

LHC

Beams: **p to Pb**
p+p $\sqrt{s}$ = **14 TeV**
p+Pb $\sqrt{s}$ = **8.8 TeV**
Pb+Pb $\sqrt{s}$ = **5.5 TeV**

Central Pb+Pb: $T \sim 3.5\,T_c$

Detectors:
ALICE ATLAS CMS

4 weeks / year physics
Average luminosity 5 * 10^{26} $cm^{-2}\,s^{-1}$
Pb+Pb luminosity/year 500 μb^{-1}

$\sigma\,(J/\psi)_{LHC} = \sigma\,(J/\psi)_{RHIC}$ * **13**
$\sigma\,(Y)_{LHC} = \sigma\,(Y)_{RHIC}$ * **55**

$N_{cc} \sim 115$ $N_{bb} \sim 5$ (central)

RHIC II

Beams: **p to U**
All combinations $\sqrt{s}$ = **22-200 GeV**

Central Au+Au: T ~ 2 T_c

Detectors:
PHENIX STAR eRHIC detector?

12 weeks / year physics (split runs)
Average luminosity 7 * 10^{27} cm^{-2} s^{-1}
Au+Au lum/year 18,000 μb^{-1}

$Lint_{RHIC}/Lint_{LHC}$ = **36**

N_{cc} ~ 10 N_{bb} ~ 0.05 (central)

LHC

Beams: **p to Pb**
p+p $\sqrt{s}$ = **14 TeV**
p+Pb $\sqrt{s}$ = **8.8 TeV**
Pb+Pb $\sqrt{s}$ = **5.5 TeV**

Central Pb+Pb: T ~ 3.5 T_c

Detectors:
ALICE ATLAS CMS

4 weeks / year physics
Average luminosity 5 * 10^{26} cm^{-2} s^{-1}
Pb+Pb luminosity/year 500 μb^{-1}
$\sigma(J/\psi)_{LHC} = \sigma(J/\psi)_{RHIC}$ * **13**
$\sigma(\Upsilon)_{LHC} = \sigma(\Upsilon)_{RHIC}$ * **55**

N_{cc} ~ 115 N_{bb} ~ 5 (central)

RHIC-II - Selected Heavy Flavor Yields

All numbers are first rough estimates (including trigger and reconstruction efficiencies) for 12 weeks physics run ($\int L_{eff}\, dt \sim 18\ nb^{-1}$)

Signal	RHIC Exp.	Obtained	RHIC I (>2008)	RHIC II	RHIC-II/R2D	LHC/ALICE[+]
$J/\psi \rightarrow e^+e^-$	PHENIX	~80	3,300	45,000	4,300,000	9,500
$J/\psi \rightarrow \mu^+\mu^-$		~7000	29,000	395,000	4,300,000	740,000
$\Upsilon \rightarrow e^+e^-$	STAR	-	830	11,200	39,000	2,600
$\Upsilon \rightarrow \mu^+\mu^-$	PHENIX	-	80	1,040	39,000	8,400
$B \rightarrow J/\psi \rightarrow e^+e^-$	PHENIX	-	40	570	67,000	N/A
$B \rightarrow J/\psi \rightarrow \mu^+\mu^-$		-	420	5,700	67,000	N/A
$\chi_c \rightarrow e^+e^-\gamma$	PHENIX	-	220	2,900*	670,000	N/A
$\chi_c \rightarrow \mu^+\mu^-\gamma$		-	8,600	117,000*	670,000	N/A
$D \rightarrow K\pi$	STAR	$\sim 0.4 \times 10^6$ (S/B~1/600)	30,000**	30,000**	N/A	8000

* Large backgrounds, quality uncertain as yet
** Running at 100 Hz min bias
+ 1 month (= year), P. Crochet, EPJdirect A1, a (2005) and private comm.

T. Frawley, PANIC'05, RHIC-II Satellite Meeting

How do we Rate the Physics Topics?

We have divided the most important heavy flavor topics into two groups.

The **A list** contains topics that **drive the program**. These have a high probability of providing a clear window on an important question.

The **B list** contains topics that **may** provide insights, or even breakthroughs, but do not qualify as program drivers because the connection of observable to physics question is strongly model dependent, or it is unclear if the answer will be informative, or ....

The A list - the program drivers

Topic	Observables	Connection
Deconfinement	ψ' and χ_c R_{AA}	Excited charmonium melts?
	J/ψ R_{AA} vs p_T	Evidence of charm coalescence?
	J/ψ R_{AA} vs y	Evidence of charm coalescence?
	J/ψ v_2 vs p_T	Not suppressed at high p_T?
	Y family R_{AA}	Y(3S) disappears?
		Y(2S) suppressed like J/ψ?
		Y(1S) unsuppressed?
Energy density	c & b leptons R_{AA}	Energy loss of heavy quarks
	$B \to J/\psi \to$ dileptons	Energy loss of b quarks
	$D \to K\pi$	Energy loss of c quarks
	J/ψ tagged jets	Energy loss of gluon jets
Transport	c & b leptons v_2	Thermalization of heavy quarks

The B list

Topic	Observables	Connection
Deconfinement	J/ψ polarization	Evidence of charm coalescence?
Energy density	c & b tagged jets	Energy loss of heavy quarks

Summary & Conclusions

- Heavy Flavor Physics at RHIC teaches us about:
  - Deconfinement
  - Thermalization
  - Transport properties of the medium
- Heavy Flavor Physics at RHIC is just at the beginning
  - Already the first glimpses point to new physics
    - Charm suppression at high-p_T
    - J/ψ: suppression + recombination
    - Cross sections larger than NLO predictions
- RHIC-II luminosity & detector upgrades dramatically expand capabilities and thus our understanding
  - Study sequential suppression of many quarkonium states
  - Evaluate effects: feed down, absorption, recombination
  - Study D, B production and suppression in the medium
  - Study thermalization via charm and quarkonium flow
- Still challenging:
  - Correlation measurements, χ_b impossible?

Backup Slides

Quarkonia – RHIC-II Goals and Requirements

Physics Motivation	Probes	Studies	Requirements
Baseline	J/ψ, ψ', ϒ(1S), ϒ(2S), ϒ(3S) through μμ and ee decay channels	Rapidity $y(x_F)$ and p_T spectra in AA, pA, pp as a function of A, $\sqrt{s}$	High luminosity and acceptance. High resolution to resolve ϒ states
Deconfinement & Initial Temperature	J/ψ, ψ', ϒ(1S), ϒ(2S), ϒ(3S)	Melting patterns of quarkonia states	Extract suppression mechanism taking into account: feed down, nuclear absorption, and recombination
Properties of the medium	High-p_T J/ψ	R_{AA}: Dissociation ↔ Quenching	High luminosity
Thermalization &Transport properties of the Medium	J/ψ	J/ψ flow (v_2) as a function of A, $\sqrt{s}$ Recombination: y and $\langle p_T^2 \rangle$	High luminosity to obtain good statistics in short time (A, √s scans)

Quarkonia – RHIC-II Goals and Requirements

In order to extract the desired suppression signals the following measurements have to be achieved:

Topic	Studies	Requirements
Nuclear effects • shadowing • absorption	Quarkonia in pp, pA: • x_2, x_F dependence • A dependence • rapidity distributions over wide range	Large y coverage Forward coverage to high x_F
Suppression vs. Recombination	• charm production $d\sigma/dp_T dy$ • v_2 of J/ψ • p_T dependence of suppression	High resolution vertex detectors
Contribution from feed down	Measure χ_c at least in pp and pA	Photon detection at mid and forward rapidity, high luminosity, good energy & momentum resolution to minimize background
Quarkonium production	pA: χ_c / J/ψ A-dependence J/ψ polarization (?)	As above Large acceptance for cos θ^*

Open Heavy Flavor – RHIC-II Goals and Requirements

Physics Motivation	Probes	Studies	Requirements
Baseline	D/B mesons, non-photonic electrons	• Rapidity $y(x_F)$ and p_T spectra in AA, pA as a function of A, √s	High Luminosity High resolution vertex detectors ($c\tau(D) \sim$ 100-300 μm) High-p_T PID ($D \rightarrow K\pi$)
Thermalization, Transport properties of the medium	D mesons, B? non-photonic electrons (D+B)	Elliptic flow v_2 p_T spectra	as above
Properties of the medium Initial conditions	D, B ($B \rightarrow J/\psi + X$) mesons, non-photonic electrons	$R_{AA}(p_T)$, R_{CP} of D , B as a function of p_T for various √s	as above
Properties of the medium Heavy Flavor Production	D mesons, non-photonic electrons	Correlations: • charm-charm • charm-hadron • J/ψ-hadron	**HIGH** luminosity (eff^2 !) Large coverage Trigger ?

The Upgraded PHENIX Detector

Charged Particle Tracking:

- Drift Chamber
- Pad Chamber
- Time Expansion Chamber/TRD
- Cathode Strip Chambers(Mu Tracking)
- Forward Muon Trigger Detector
- Si Vertex Tracking Detector- Barrel (Pixel + Strips)
- Si Vertex Endcap (mini-strips)

Particle ID:

- Time of Flight
- Ring Imaging Cerenkov Counter
- TEC/TRD
- Muon ID (PDT's)
- Aerogel Cerenkov Counter
- Multi-Resistive Plate Chamber Time of Flight
- Hadron Blind Detector

Calorimetry:

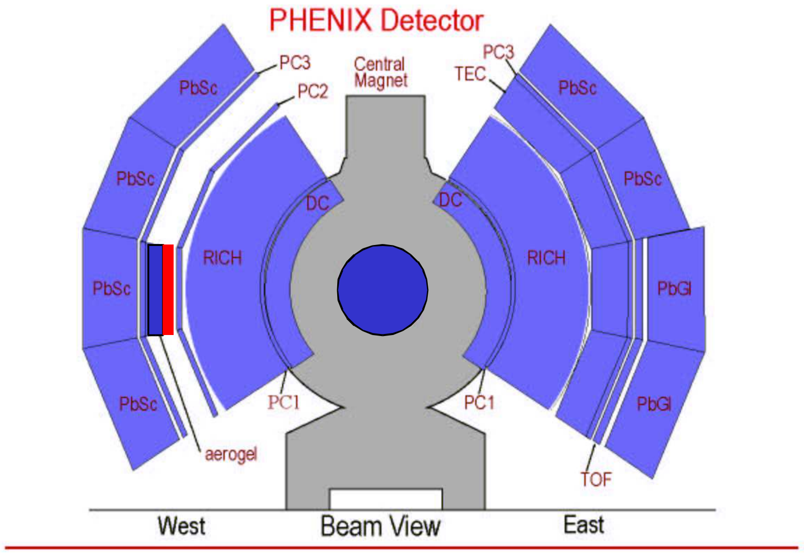
- Pb Scintillator
- Pb Glass
- Nose Cone Calorimeter

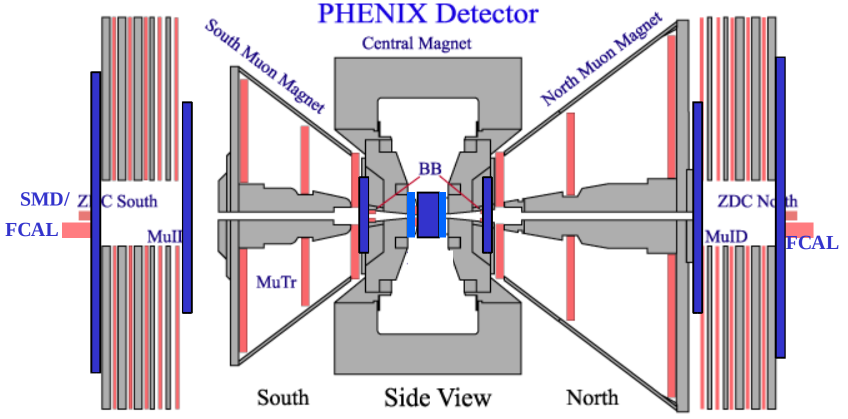
Event Characterization:

- Beam-Beam Counter
- Zero Degree Calorimeter/Shower Max Detector
- Forward Calorimeter

Data Acquisition:

- DAQ Upgrade





STAR Upgrades